

# The “quiescent” black hole in M87

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## ABSTRACT

It is believed that most giant elliptical galaxies possess nuclear black holes with masses in excess of  $10^8 M_\odot$ . Bondi accretion from the interstellar medium might then be expected to produce quasar-like luminosities from the nuclei of even quiescent elliptical galaxies. It is a puzzle that such luminosities are *not observed*. Motivated by this problem, Fabian & Rees have recently suggested that the final stages of accretion in these objects occurs in an advection-dominated mode with a correspondingly small radiative efficiency. Despite possessing a long-known active nucleus and dynamical evidence for a black hole, the low radiative and kinetic luminosities of the core of M87 provide the best illustration of this problem. We examine an advection-dominated model for the nucleus of M87 and show that accretion at the Bondi rate is compatible with the best known estimates for the core flux from radio through to X-ray wavelengths. The success of this model prompts us to propose that FR-I radio galaxies and quiescent elliptical galaxies accrete in an advection dominated mode whereas FR-II type radio-loud nuclei possess radiatively efficient thin accretion disks.

**Key words:** galaxies: individual: M87, galaxies: active, accretion, accretion discs

## 1 INTRODUCTION

There is strong evidence that most giant elliptical galaxies should possess nuclear supermassive black holes, relics of an earlier quasar phase. Quasar counts and integrated luminosities suggest masses above  $10^8 - 10^9 M_\odot$ . Given this fact, there is a major puzzle surrounding quiescent giant ellipticals which was first illuminated by Fabian & Canizares (1988). A massive black hole in the centre of an elliptical galaxy would accrete from the interstellar medium (which forms a hot hydrostatic atmosphere in the potential well of the galaxy). The accretion rate would be expected to be at least that given by Bondi’s spherical accretion formula (Bondi 1952). If the resulting accretion flow into the hole proceeds via a standard accretion disk (with a radiative efficiency of  $\sim 10$  per cent), all such nuclei should be seen to possess quasar-like luminosities. This is contrary to observation.

The nearby giant elliptical galaxy M87 (NGC 4486) might be considered a counter example because it has long been known to host an active nucleus that powers a jet and the giant radio lobes of Virgo A. Furthermore, *HST* observations have now provided a direct dynamical determination of the nuclear black hole mass of  $M \approx 3 \times 10^9 M_\odot$  (Ford

et al. 1995; Harms et al. 1995). In fact, M87 illustrates the problem of quiescent black holes in giant ellipticals and, we suggest, illuminates the solution. Qualitative evidence for the relative quiescence of M87 comes from a comparison to the quasar 3C273, which presumably contains a black hole of comparable mass. While both have core, jet and lobe emission, the luminosity of M87 in all wavebands falls 5 orders of magnitude below that of 3C273 (see below).

The contrast between M87 and 3C273 cannot be completely ascribed to a smaller mass accretion rate in the former, as can be seen by an estimate of the Bondi accretion rate in M87. Imaging X-ray observations provide information on the hot interstellar medium (ISM). A deprojection analysis of data from the *ROSAT* High Resolution Imager (HRI) shows that the ISM has a central density  $n \approx 0.5 \text{ cm}^{-3}$  and sound speed  $c_s = 500 \text{ km s}^{-1}$  (C. B. Peres, private communication). The resulting Bondi accretion rate onto the central black hole is  $\dot{M} \sim 0.15 M_\odot \text{ yr}^{-1}$ . Following standard practice, we define a dimensionless mass accretion rate by

$$\dot{m} = \frac{\dot{M}}{\dot{M}_{\text{Edd}}}, \quad (1)$$

where  $\dot{M}$  is the mass accretion rate and  $\dot{M}_{\text{Edd}}$  is the Eddington accretion rate assuming a radiative efficiency of  $\eta = 0.1$ . For M87, the Eddington limit is  $L_{\text{Edd}} \approx 4 \times 10^{47} \text{ erg s}^{-1}$  corresponding to  $\dot{M}_{\text{Edd}} = 65 M_\odot \text{ yr}^{-1}$ . The Bondi accretion

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rate corresponds to  $\dot{m} \sim 2 \times 10^{-3}$  and so, assuming a radiative efficiency  $\eta = 0.1$ , would produce a radiative luminosity of  $L \sim 8 \times 10^{44} \text{ erg s}^{-1}$ . Observationally, the nucleus is orders of magnitude less active. The observed radiative power does not exceed  $L_{\text{obs}} \sim 10^{42} \text{ erg s}^{-1}$  (Biretta, Stern & Harris 1991; also see Section 2 of this letter) and the time-averaged kinetic luminosity of the jet cannot exceed much more than  $L_K \sim 10^{43} \text{ erg s}^{-1}$  (Reynolds et al. 1996).

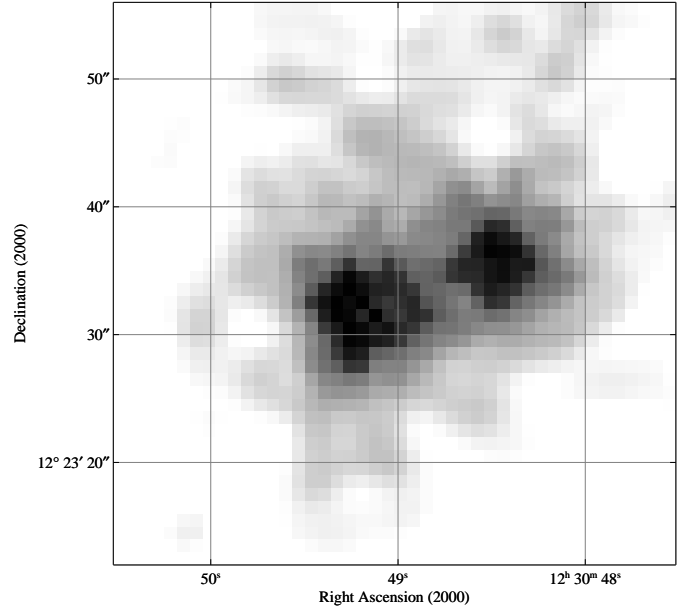
The recent interest in advection-dominated accretion disks (Narayan & Yi 1995; Abramowicz et al. 1995; Narayan, Yi & Mahadevan 1995) prompted Fabian & Rees (1995) to suggest that such disks exist around the nuclear black holes in quiescent giant elliptical galaxies. In this mode of accretion, the accretion flow is very tenuous and so a poor radiator. (The possibility of similarly tenuous ‘ion-supported tori’ had been discussed in the context of radio galaxies by Rees et al. 1982 and for the Galactic centre by Rees 1982). Much of the energy of the accretion flow cannot be radiated and is carried through the event horizon. Fabian & Rees (see also Mahadevan 1996) realised that the resulting low radiative efficiency provides a possible solution to the elliptical galaxy problem described above. They identify the weak parsec-scale radio cores seen in most elliptical galaxies (Sadler et al. 1989; Wrobel & Heeschen 1991; Slee et al. 1994) with synchrotron emission from the plasma of the advection-dominated disks (ADD).

In this *Letter* we present a detailed examination of the possibility that the massive black hole in M87 accretes via an ADD. In particular, we compute the spectrum of the ADD and show that it is consistent with the observations for physically reasonable mass accretion rates. In Section 2 we compile data from the literature on the full-band spectrum of the core of M87 and present some additional data on the X-ray flux from the core. Care is taken to limit the effect of contaminating emission from the jet and/or the galaxy. Despite this, the spectrum we obtain must still be considered as a set of upper limits on the spectrum of the accretion flow with the non-thermal emission from the jet representing the main contaminant. We make a direct comparison to the quasar 3C 273. Section 3 describes some details of our ADD model spectrum calculation. Section 4 compares this model spectrum with the data and finds that accretion rates comparable with the Bondi rate do not overproduce radiation and are thus acceptable. Section 5 discusses some further astrophysical implications of this result.

## 2 THE SPECTRUM OF THE CORE EMISSION

### 2.1 The M87 data

In order to examine the nature of the accretion flow in M87, we have attempted to compile the best observational limits on the full band spectrum of the core emission. Our aim is to obtain good observational limits on the core flux over a wide range of frequencies rather than to compile a comprehensive list of all previous observations. For radio through optical, we use the highest spatial resolution data available from the literature in order to minimize the contribution to the flux from the synchrotron emitting jet and the galaxy. However, contributions from the jet and the underlying galaxy are unavoidable and so the derived spectrum should be considered



**Figure 1.** The core regions of M87/Virgo as imaged in a 14ks exposure with the *ROSAT* HRI. Two distinct sources are seen embedded in general diffuse emission. The easternmost source corresponds to the core of M87 whereas the western source coincides with the brightest knot within the jet (knot-A). The diffuse emission is from the hot interstellar medium.

an upper limit to that of the accretion flow at the core of M87. These data are summarized in Table 1.

The situation with regard to hard X-ray emission from the AGN in M87 has been confused and deserves some comment. The overall X-ray emission from M87 is highly extended and clearly of thermal origin, arising from diffuse gas with average  $kT \sim 3 \text{ keV}$ . Several observations with wide-field X-ray instruments indicated the presence of an X-ray power law component, which was suggested to be associated with the nuclear region of M87 (Lea et al. 1981, Matsumoto et al. 1996 and references therein), but were probably confused by the hard X-ray emission from the nearby Seyfert 2 galaxy NGC 4388 (Hansen 1990; Takano & Koyama 1991). A reanalysis of soft X-ray *Einstein* HRI observations with arc second resolution by Biretta, Stern & Harris (1991) found emission from a core point source at a level more than an order of magnitude below that found by the wide-field X-ray instruments.

We have examined the *ROSAT* HRI and ASCA data sets in order to constrain further the nuclear X-ray flux of M87. The *ROSAT* data were retrieved from the public archive situated at the GODDARD SPACE FLIGHT CENTER and result from a 14 200 s exposure performed on 1992-June-7. Figure 1 shows the *ROSAT* HRI image of the central regions of M87. Emission from the core and knot-A ( $\sim 10$  arcsecs west of the core) are clearly separated from each other as they were in the *Einstein* HRI image (Biretta, Stern & Harris 1991). The *ROSAT* HRI count rate is  $0.093 \text{ cts s}^{-1}$  (determined using the XIMAGE software package). Assuming the spectrum to be a power-law with a canonical photon index  $\Gamma = 1.7$  (Mushotzky, Done & Pounds 1993) modified

**Table 1.** Summary of data for the core of M87.

Frequency $\nu$ (Hz)	Resolution (milliarcsecs)	$\nu F_\nu$ ( $10^{-14}$ erg s $^{-1}$ cm $^{-2}$ )	reference	notes
$1.7 \times 10^9$	5	1.65	Reid et al. (1989)	VLBI
$5.0 \times 10^9$	0.7	1.0	Pauliny-Toth et al. (1981)	VLBI
$2.2 \times 10^{10}$	0.15	4.8	Spencer & Junor (1986)	VLBI
$1.0 \times 10^{11}$	0.1	8.7	Bääth et al. (1992)	VLBI
$7 \times 10^{14}$	50	200	Harms et al. (1994)	HST
$2.4 \times 10^{17}$	$4 \times 10^3$	85	Biretta et al. (1991)	<i>Einstein</i> HRI
$2.4 \times 10^{17}$	$4 \times 10^3$	160	this work	<i>ROSAT</i> HRI
$4.8 \times 10^{17}$	$2 \times 10^5$	$\leq 700$	this work	<i>ASCA</i>

by the effects of Galactic absorption (with column density  $N_H = 2.5 \times 10^{20}$  cm $^{-2}$ ; Stark et al. 1992), this count rate implies a flux density at 1 keV of  $F(1 \text{ keV}) = 0.67 \mu\text{Jy}$ . This result is fairly insensitive to choosing a different power-law index.

ASCA observed M87 during the PV phase: 12 600 s of good data were obtained in 1993 June. Independent analysis was performed by Matsumoto et al. (1996). A 3 arcmin radius circle centered on the nucleus of M87 contains approximately 50 000 counts in a single SIS detector. We performed a variety of fits to the spectrum in the central regions, incorporating multiple thermal components, possible excess low-energy absorption, and possible cooling-flow emission. In no case does the addition of a power law component give a noticeable improvement in the fit (we fix the power law index at  $\Gamma = 1.7$ ). Our limit (at 90 per cent confidence) is listed in Table 1. It is somewhat below the value (whose significance is not stated) reported by Matsumoto et al. (1996). The *Einstein* and *ROSAT* HRI fluxes differ somewhat. Given the well known variability of AGN in the X-ray band (Mushotzky, Done & Pounds 1993), time variability is a plausible explanation for this difference.

High resolution VLBI observations probably provide the strongest constraints on the core emission (since they can separate the core emission from knots of jet emission even within the innermost parsec of the source). High resolution optical (HST) and X-ray (*ROSAT* HRI) measurements are likely to be free of galactic contamination but may still possess a significant contribution from the inner jet. Sub-mm and far-IR studies provide uninteresting limits on the core flux: the comparatively poor spatial resolution leads to severe contamination from galactic emission (predominantly thermal emission by dust).

## 2.2 The 3C 273 data

For comparison with M87, the open squares on Fig. 2 show data for the radio-loud quasar 3C 273. These data are from the compilation of Lichti et al. (1995) and are simultaneous or near-simultaneous. Much of this emission is likely to originate from the jet and be relativistically beamed. However, the fact that we see a big blue bump and optical/UV emission lines from 3C 273 implies that a significant part of the optical/UV emission is unbeamed and likely to originate from the accretion flow.

## 3 THE ADVECTION-DOMINATED MODEL

It is well known that sub-Eddington accretion can proceed via a thin accretion disk (see review by Pringle 1981 and references therein). Such disks are characterised by being radiatively efficient so that the energy generated by viscous dissipation is radiated locally. As a consequence, such disks are cold in the sense that the gas temperature is significantly below the virial temperature. However, for sufficiently low mass accretion rates ( $\dot{m} < \dot{m}_{\text{crit}} \approx 0.3\alpha^2$ , where  $\alpha$  is the standard disk viscosity parameter) there is another stable mode of accretion (see Narayan & Yi 1995 and references therein). In this second mode, the accretion flow is very tenuous and, hence, a poor radiator. The energy generated by viscous dissipation can no longer be locally radiated – a large fraction of this energy is advected inwards in the accretion flow as thermal energy and, eventually, passes through the event horizon. These are known as advection-dominated disks (ADDs).

For convenience, we rescale the radial co-ordinate and define  $r$  by

$$r = \frac{R}{R_{\text{Sch}}}, \quad (2)$$

where  $R$  is the radial coordinate and  $R_{\text{Sch}}$  is the Schwarzschild radius of the hole. It is an important feature of ADDs that, in the region  $r < 1000$ , the ions and electrons do not possess the same temperature. The ions attain essentially the virial temperature. They couple weakly via Coulomb interactions to the electrons which, due to various cooling mechanisms, possess a significantly lower temperature.

By assuming that the system is undergoing advection-dominated accretion, we can predict the radio to X-ray spectrum of the accretion flow. Since the gas is optically-thin, the emission in different regions of the spectrum is determined by synchro-cyclotron, bremsstrahlung and inverse Compton processes. The amount of emission from these different processes and the shape of the spectrum can be determined as a function of the model variables: the viscosity parameter,  $\alpha$ , the ratio of magnetic to total pressure,  $\beta$ , the mass of the central black hole,  $M$ , and the accretion rate,  $\dot{m}$ . For the moment, we take  $\alpha = 0.3$  and  $\beta = 0.5$  (i.e. magnetic pressure in equipartition with gas pressure), although see discussion in Section 5. The electron temperature at a given point in the ADD,  $T_e$ , can then be determined self-consistently for a given  $\dot{m}$  and  $M$  by balancing the heating of the electrons by the ions against the various radia-

tive cooling mechanisms. Within  $r < 1000$ , it is found that  $T_e \approx 2 \times 10^9$  K. To determine the observed spectrum, we must integrate the emission over the volume and take account of self-absorption effects. We have taken the inner radius of the disk to correspond with the innermost stable orbit around a Schwarzschild black hole,  $r_{in} = 3$ , and the outer radius to be  $r_{out} = 10^3$ . The spectrum is rather insensitive to the choice of  $r_{out}$  since most of the radiation originates within  $r_{out}$ . Details of the model, which is based on that of Narayan & Yi (1995), can be found in Di Matteo & Fabian (1996).

In Fig. 2 we show the spectrum of the advection-dominated disk for  $M = 3 \times 10^9 M_\odot$  and  $\dot{m} = 10^{-3.5}, 10^{-3.0}$  and  $10^{-2.5}$ . The peak in the radio band is due to synchro-cyclotron emission by the thermal electrons in the magnetic field of the plasma. The X-ray peak is due to thermal bremsstrahlung emission. The power-law emission extending through the optical band is due to Comptonization of the synchro-cyclotron emission: more detailed calculations show this emission to be comprised of individual peaks corresponding to different orders of Compton scattering. The positions at which the synchrotron and bremsstrahlung peaks occur and their relative heights depend on the parameters of the model. The synchrotron radiation is self-absorbed and gives a black body spectrum, up to a critical frequency,  $\nu_c$ . Above the peak frequency the spectrum reproduces the exponential decay in the emission expected from thermal plasma (Mahadevan & Narayan 1996). The bremsstrahlung peak occurs at the thermal frequency  $\nu \sim k_B T_e / h$ .

#### 4 THE COMPARISON

Figure 2 demonstrates the comparison between the core data and the advection dominated disk model described above. The accretion rate for all three models shown is comparable (within an order of magnitude) to the Bondi rate. Each of these models represents a physically plausible accretion rate. The two lower model curves ( $\dot{m} = 10^{-3.5}, 10^{-3.0}$ ) are completely acceptable in the sense that they do not exceed any observational bounds. Furthermore, it can be seen that a substantial portion of the VLBI core flux may originate from an advection dominated disk. In particular two of the VLBI data points seem to reproduce almost exactly the slope of self-absorbed cyclo-synchrotron spectrum. We note that radio observations of early-type galaxy cores typically show rising or flat spectra with very similar slope ( $\approx 0.3$ ) (Slee et al. 1994), which is well accounted for by the spectrum of an ADD (Fig. 2 and Mahadevan 1996).

The core as seen in the 100 GHz VLBI data, the HST data and the *ROSAT* HRI X-ray data requires some additional component. The synchrotron jet would be a candidate for this additional component (provided the jet becomes self-absorbed at frequencies  $\nu \approx 100$  GHz or less).

Figure 2 shows the contrast between M87 and 3C 273. 3C 273 is observed to be at least 5 orders of magnitude more luminous than M87 at all wavelengths. The big blue bump in the spectrum of this quasar is often interpreted to be thermal emission from a standard thin-disk. Assuming a thin-disk efficiency of  $\eta = 0.1$ , the inferred accretion rate is  $\dot{M} \sim 50 M_\odot$ . Thus, it is possible that the mass accretion rates in M87 and 3C 273 differ by only 2 orders of magnitude

despite the fact that the luminosities differ by 5–6 orders of magnitude.

#### 5 SUMMARY AND DISCUSSION

We conclude that accretion from the hot gas halo at rates comparable with the Bondi rate is compatible with the low-luminosity of this core provided the final stages of accretion (where most of the gravitational energy is released) involve an advection dominated disk. This is in complete accord with the suggestion of Fabian & Rees (1995). An important test of this model will be the micro-arcsec radio imaging such as is promised by the VLBI Space Observatory Program (VSOP). This will provide the capability to image the core of M87 on scales comparable to the Schwarzschild radius of the black hole. Any advection-dominated disk should be directly revealed as a synchrotron self-absorbed structure with a position angle that is perpendicular to the jet axis.

In constructing our ADD model, we have assumed a large value of the viscosity parameter,  $\alpha = 0.3$ . It should be stressed that the ADD model remains compatible with the core data even for smaller values of  $\alpha$ . For  $\alpha < 0.3$ , we have to postulate that the magnetic field in the disk is below its equipartition value (i.e.  $\beta > 0.5$ ) in order that an ADD with  $\dot{m} \sim 10^{-3}$  does not violate the VLBI limits. Given the recent MHD disk simulations of Stone et al. (1996), this is not an unreasonable relaxation of our basic assumptions. In fact, all that is required is that  $\alpha$  is sufficiently large so as to make the ADD solution accessible for the accretion rates present in M87. If  $\dot{m} \sim 10^{-3}$ , then we require  $\alpha \gtrsim 0.06$ .

The consistency of this model with the data allows us to explore some astrophysical implications of ADDs in giant elliptical galaxies. Rees et al. (1982) have argued that electromagnetic extraction from black holes surrounded by ion-supported tori (which share many of the basic physical properties of ADDs) can power relativistic jets in radio galaxies. The jets can be collimated in the inner regions of the ion-supported torus. If we apply the Blandford-Znajek (1977) mechanism to M87, we predict that the amount of energy extracted from a Kerr black hole is of the order of

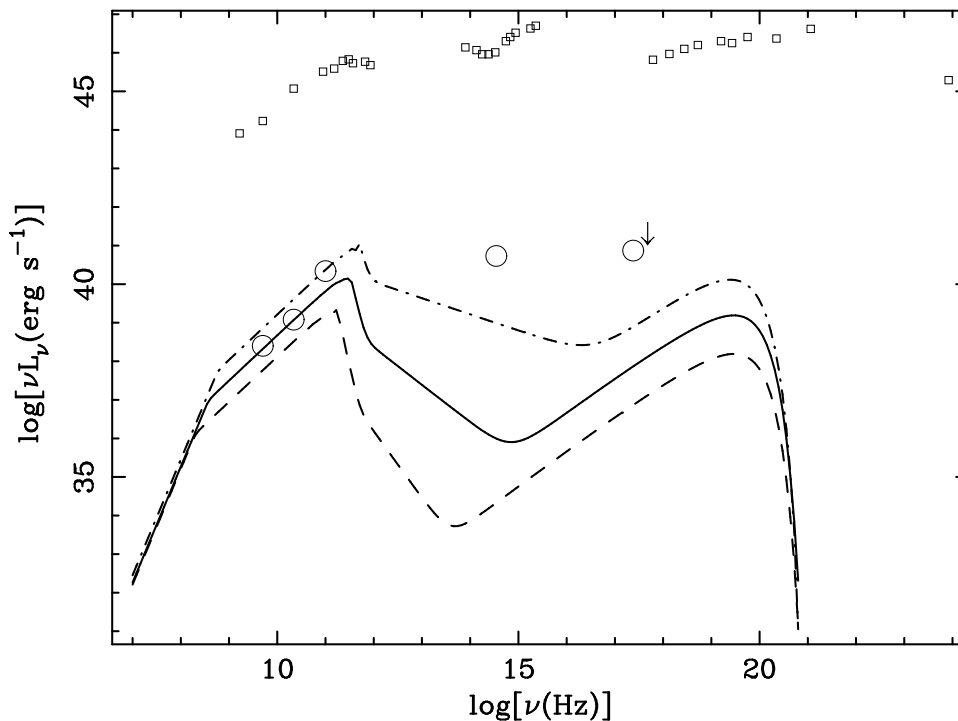
$$L_{EM} \approx 10^{43} \left( \frac{a}{m} \right)^2 B_2^2 M_9^2 \text{ erg s}^{-1}, \quad (3)$$

where  $a < m$  is the usual angular momentum of the black hole (in dimensionless units),  $M = 10^9 M_9 M_\odot$  is the mass of the black hole ( $M_9 \approx 3$ ) and  $B = 10^2 B_2$  G is the magnetic field in the vicinity of the hole. From our model (assuming equipartition), we determine  $B$  to be

$$B_2 = 1.50 \left( \frac{r}{3} \right)^{-5/4} \left( \frac{\dot{m}}{10^{-3}} \right)^{1/2}. \quad (4)$$

This determination of  $L_{EM}$  is completely consistent with the kinetic luminosity of M87 jet ( $L_K \sim 10^{43} \text{ erg s}^{-1}$ ) obtained by Reynolds et al. (1996).

ADDs may be relevant to the creation of a unified model for radio-loud AGN. We are suggesting that M87, a classic FR-I radio source, possesses an ADD. However, *ASCA* observations of broad iron  $K\alpha$  fluorescence lines in the two FR-II sources 3C 390.3 (Eracleous, Halpern & Livio 1996) and 3C 109 (Allen et al. 1996) strongly point to the presence of standard cold (thin) accretion disks in these objects. This



**Figure 2.** Spectra of M87 calculated with an advection-dominated flow extending from  $r_{min} = 3$  to  $r_{max} = 1000$ . The parameters are  $m = 3 \times 10^9$ ,  $\alpha = 0.3$ ,  $\beta = 0.5$ . Three models are shown: (i)  $\dot{m} = 10^{-3.5}$ -dashed line, (ii)  $\dot{m} = 10^{-3}$ -solid line, (iii)  $\dot{m} = 10^{-2.5}$ -dot-dashed line. The circles and squares represent various measurements of the spectrum of M87 and 3C 273, respectively, taken from different the references explained in the text. For M87, a distance of 16 Mpc is assumed, whereas for 3C 273 we have taken a Hubble constant of  $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and a deceleration parameter of  $q_0 = 0.0$ . In our model, the spectrum of M87 would lie only 2 decades below that of 3C273 if it had a standard, rather than advection-dominated, disk.

leads to the speculation that the FR-I/FR-II dichotomy is physically the dichotomy between advection-dominated and standard disks: i.e. FR-I sources possess ADDs whereas FR-II sources possess ‘standard’ thin accretion disks. In this sense, the accretion disks in FR-II sources and Seyfert nuclei would be intrinsically similar (Seyfert nuclei also display broad iron emission lines that are believed to originate from the central regions of a thin accretion disk.) We note that a very similar unification scheme (in the context of ion-supported tori versus thin accretion disks) has been discussed by Begelman, Blandford & Rees (1984) and Begelman (1985; 1986). The only difference is the increased observational evidence.

Extending this unified scheme to all AGN, the two fundamental classes of AGN would be those with ADDs and those with thin accretion disks. Within these two classes, some currently unknown physical difference (possibly black hole spin parameter or galactic environment) would create the dichotomy between radio-loud and radio-quiet objects. It has recently been suggested that narrow emission line galaxies (NELGs) are radio-quiet nuclei possessing ADDs (Di Matteo & Fabian 1996). Within the context of our unified scheme, this leads us to identify NELG and FR-I radio galaxies as basically the same objects, differing only in the fact that FR-I objects possess radio-jets. It is interesting to note that broad optical emission lines are not ob-

served from either FR-I sources or ‘genuine’ NELG<sup>†</sup>. Indeed, optical spectroscopy of the core of M87 by the Faint Object Spectrograph (FOS) on *HST* fails to reveal broad ( $\text{FWHM} > 2000 \text{ km s}^{-1}$ )  $\text{H}\beta$  line emission (Harms et al. 1994). Thus, the presence of an ADD may preclude the formation of a broad emission line region, possibly due to the lack of any strong photoionizing continuum.

The most likely control parameter determining which mode of accretion operates is the mass accretion rate  $\dot{m}$ . The accretion could be advection-dominated at low accretion rates ( $\dot{m} < \dot{m}_{crit}$ ) and via a standard disk for larger accretion rates. The smaller radiative efficiency of ADDs provides a natural explanation for the fact that FR-I sources are of lower power than FR-II sources. However, the situation can be much more complex. The mode of accretion may depend on the thermal state of the inflowing material. In an elliptical galaxy, accretion from a hot ISM may favour the ADD mode (provided  $\dot{m}$  is sufficiently low) simply be-

<sup>†</sup> Some objects classified as NELG are known to be obscured Seyfert nuclei. The obscuration usually reveals itself at other wavelengths (e.g. via the associated X-ray absorption and/or IR bump resulting from reprocessing by the obscuring dust.) There are objects (which we called ‘genuine’ NELG) that have no evidence for obscuration but still do not show broad optical emission lines.

cause the material does not have time to cool (see a detailed discussion of this, in the context of ion-supported tori, by Begelman 1986). Furthermore, the mode of accretion could be history dependent. As discussed by Fabian & Crawford (1990), a thin disk is a prolific radiator of optical/UV radiation, so that hot infalling material would be Compton cooled by these soft photons and enter the accretion disk pre-cooled. By this mechanism, a thin disk could remain intact even if the accretion rate were to drop into the regime in which an ADD is allowed. Some catastrophic event (such as a galaxy or sub-cluster merger) would be required to make the transition from a thin disk to an ADD.

Both Fabian & Rees (1995) and Di Matteo & Fabian (1996) have suggested that ADDs are important for understanding the demise of quasars since early cosmological epochs ( $z \sim 2$ ). A decrease in the average mass accretion rate (associated with the galactic systems becoming more relaxed and mergers/interactions becoming less frequent), or an increase in the temperature of the accreting gas (perhaps due to a decrease in Compton cooling following disruption of a thin-disk) could lead quasars to undergo a transition and accrete via ADD. After the transition, the luminosity could be lower by orders of magnitude, even though the mass accretion rate may only have dropped by a relatively small fraction. Such objects would thus be undetectable at cosmological distances. This suggestion has important implications for estimates of the black hole mass. Even quiescent galaxies might contain black holes that are doubling their mass on timescales of  $\sim 10^{10}$  yr (using the parameters of M87: note that an M87-like object placed at cosmological distances would be considered to be a weakly active object). Shorter term behaviour of AGN might also reflect changes in accretion mode. It is known that radio-loud objects are not steady over cosmological timescales but undergo bursts of duration  $10^6$ – $10^8$  yr. It is normally thought that these bursts have to be caused by large changes in mass accretion rate. However, a burst could be caused by a relatively small increase in  $\dot{m}$  if that increase were sufficient to force an ADD to a thin-disk transition.

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